Search for the Enhancement of the Thermal Expansion Coefficient of Superfluid ^{4}He near T_λ by a Heat Current

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OUTLINE

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- Motivation
- Theoretical prediction
- Experimental method
- Data analysis
- Discussion

Motivation

- Why to study the superfluid transition in the presence of a heat current (Q)?
  - Superconductor carrying an electric current, but with critical fluctuations.
  - Heat current truncates divergence of the correlation length ξ
  - Physical properties become non-linear and Q-dependent
  - Model system to study non-equilibrium phase transitions and critical phenomena
  - Verify theoretical predictions based on Renormalization-Group calculation

- Why the thermal expansion coefficient?
  - To search for the enhancement by a heat current

Theoretical Prediction

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— C_P enhanced by a heat current

$$\Delta C_P(T,Q) = t^{-\alpha} f(Q/Q_c)$$

— β_P exhibits the same critical behavior as the specific heat C_P

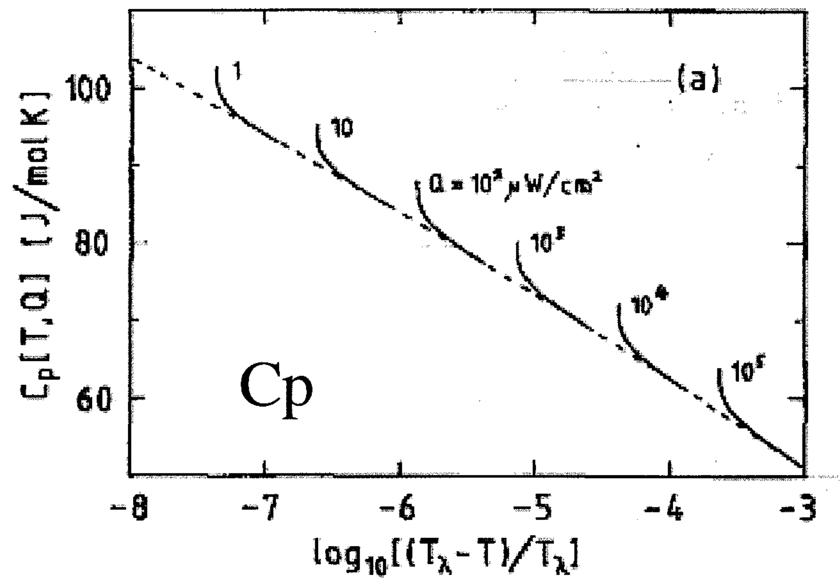
→ β_P enhanced by heat current

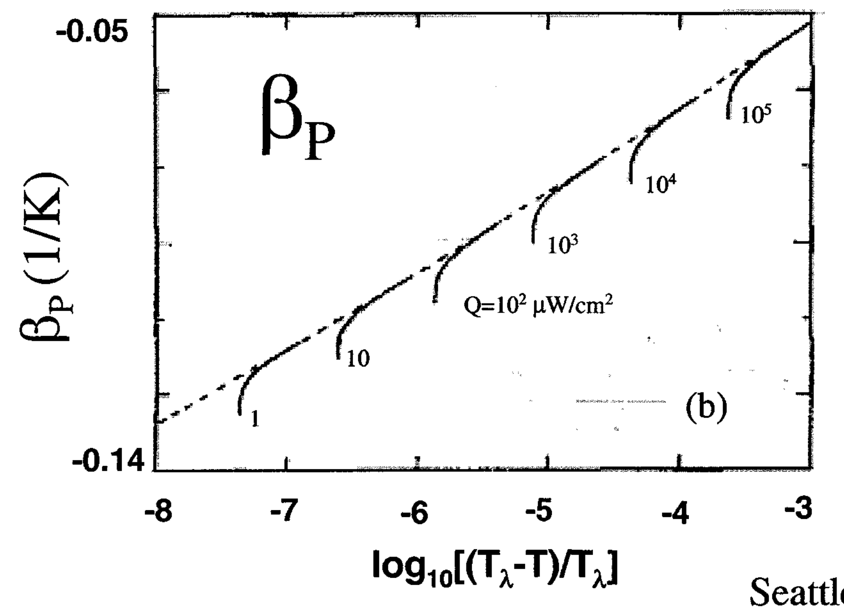
$$C_P = VT\left(\frac{\partial P}{\partial T}\right)_\lambda \beta_P + T\left(\frac{\partial S}{\partial T}\right)_\lambda$$

$$\beta_P = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P$$

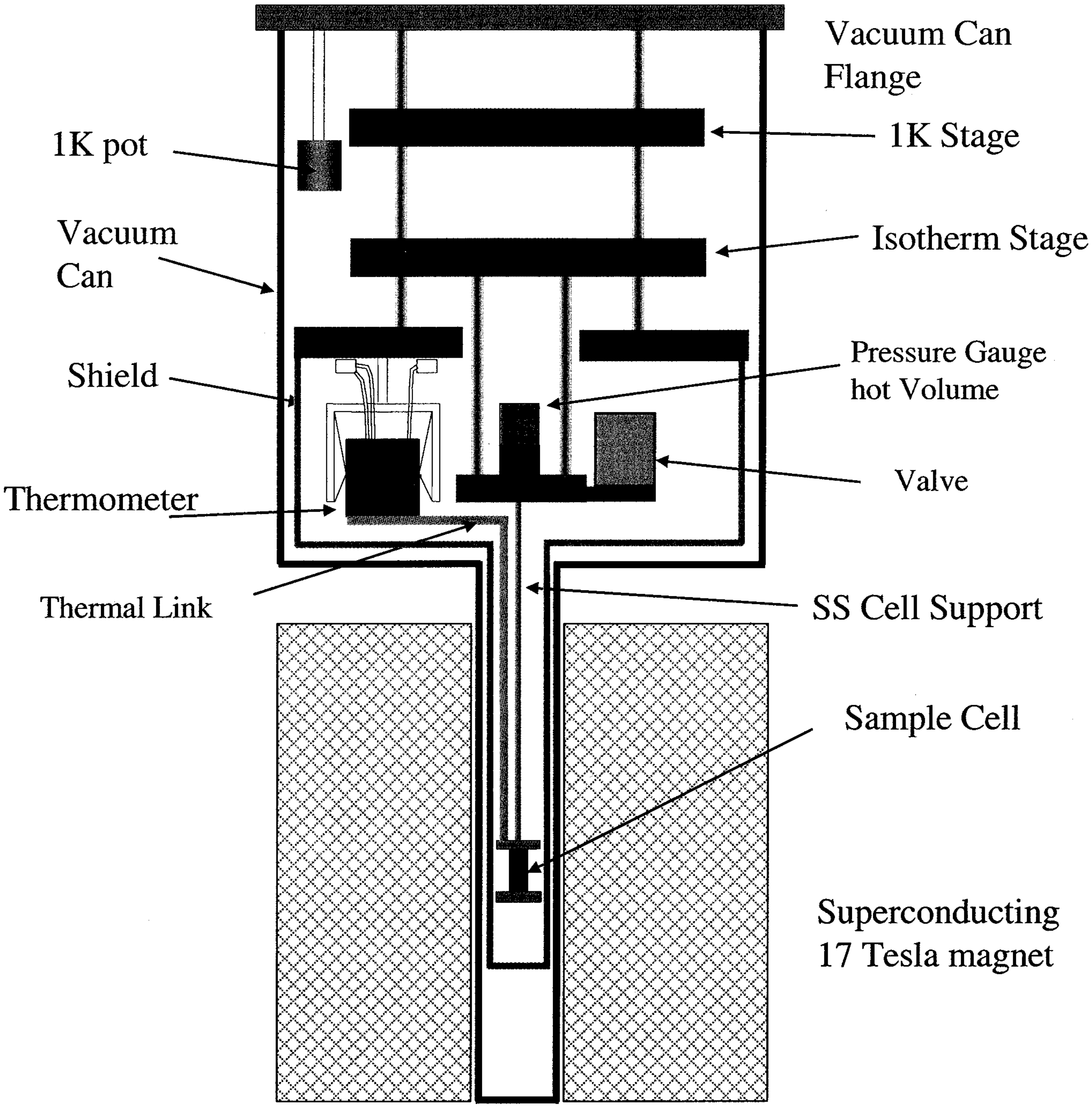
— More easily measured under pressure

Byproduct of hot volume pressure regulation





Apparatus: Low-gravity Simulator



Thermal Conductivity Cell & Pressure Regulation

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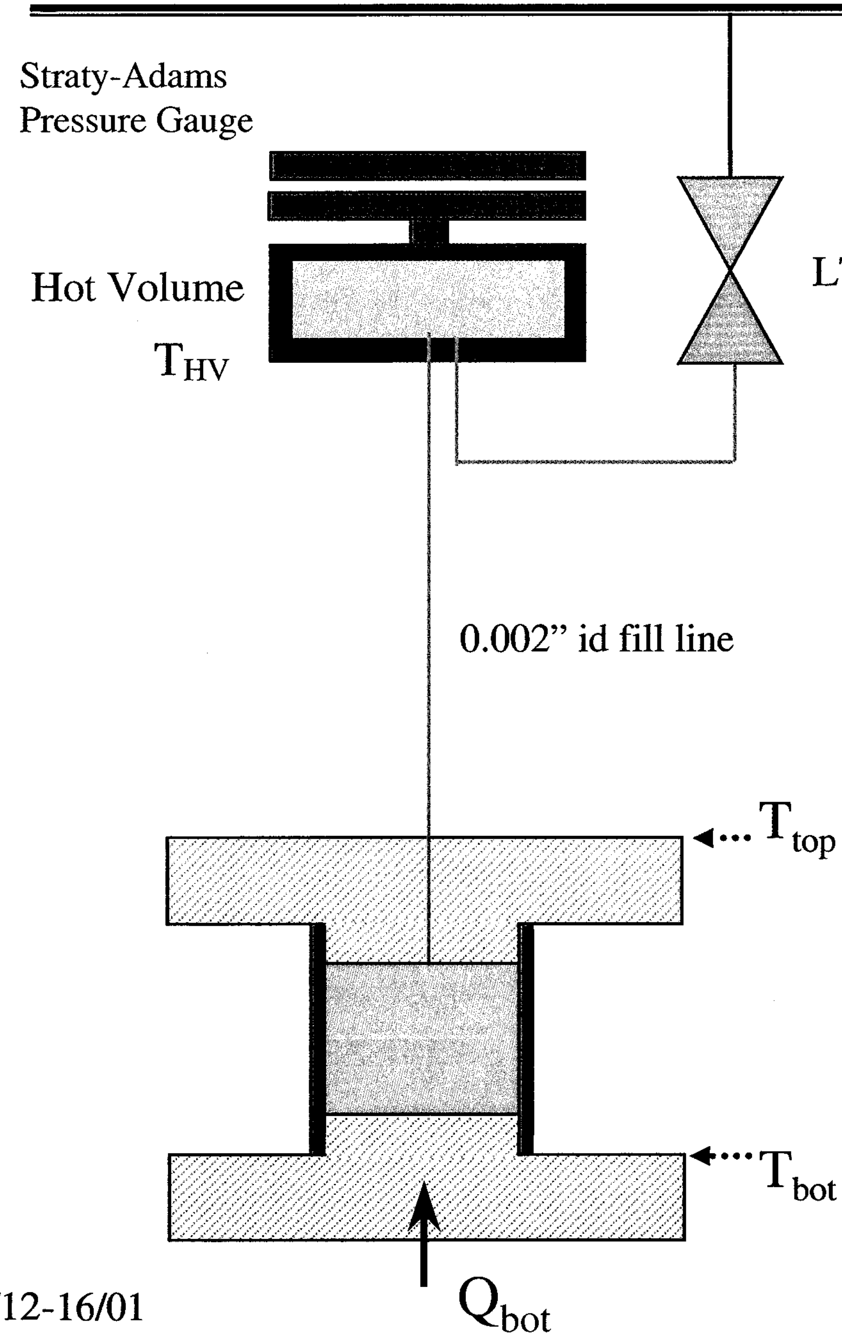


Pressure regulation:

Pressure Gauge + Hot Volume + LT Valve

Resolution: fraction of μbar (rms)

K. H. Mueller, G. Ahlers, and F. Pobell (1976)

$V_{HV} \sim V_{cell} \sim 0.1$ cc

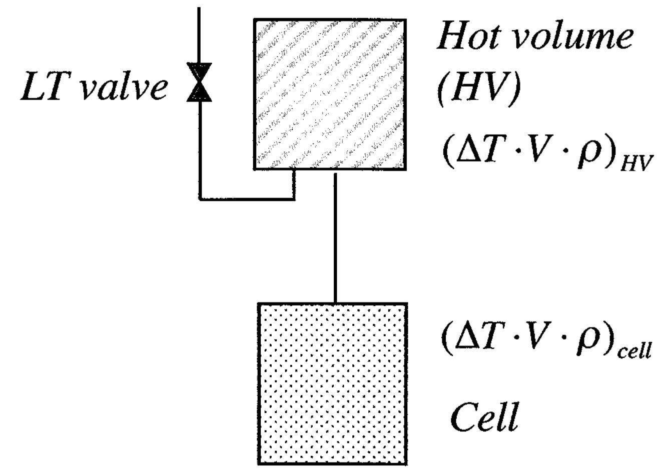
Cell Characteristics

- ✓ ***Sidewall:*** *0.004" Stainless Steel*
- ✓ ***Endcaps:*** *OFHC copper*
- ✓ ***Thermometers:*** *He-4 melting curve thermometers (MCT)*
- ✓ ***Dimensions:*** *0.5cm did., 0.5cm tall*
- ✓ ***Epoxy seal***

Hot Volume Technique

- From mass conservation ($M = M_{HV} + M_{cell}$)

$$\beta_{P,cell} = \lim_{\Delta T(cell)\to 0} - \beta_{P,HV} \frac{(\Delta T \cdot V \cdot \rho)_{HV}}{(\Delta T \cdot V \cdot \rho)_{cell}}$$

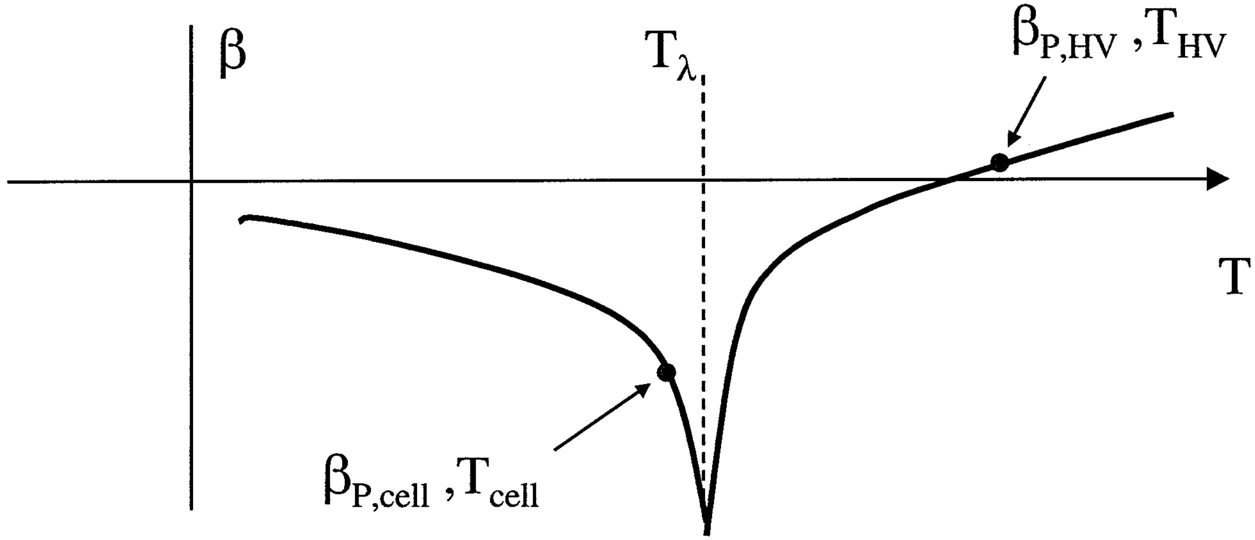


- In a ramping experiment:

$$\beta_{P,cell} \propto \beta_{P,HV} (\partial T_{HV} / \partial T_{cell})$$

Slope of the temperature plot of T_{HV} vs. T_{cell}

- To improve sensitivity, T_{HV} is chosen so that $\beta_{P,HV}$ is close to 0.



Raw Ramping Data

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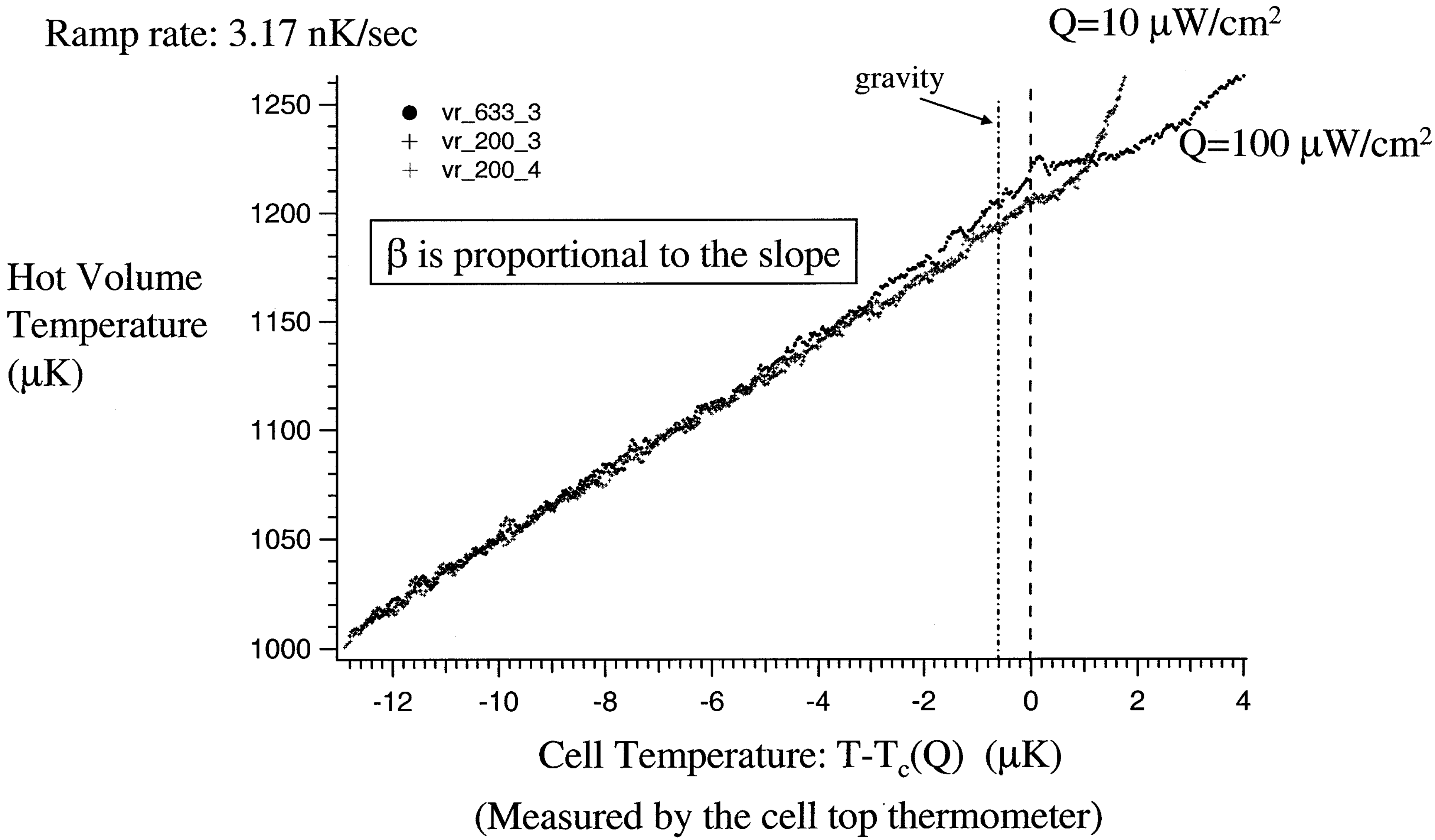
Cell Pressure = 1 bar
Ramp rate: 3.17 nK/sec



Time Series Data

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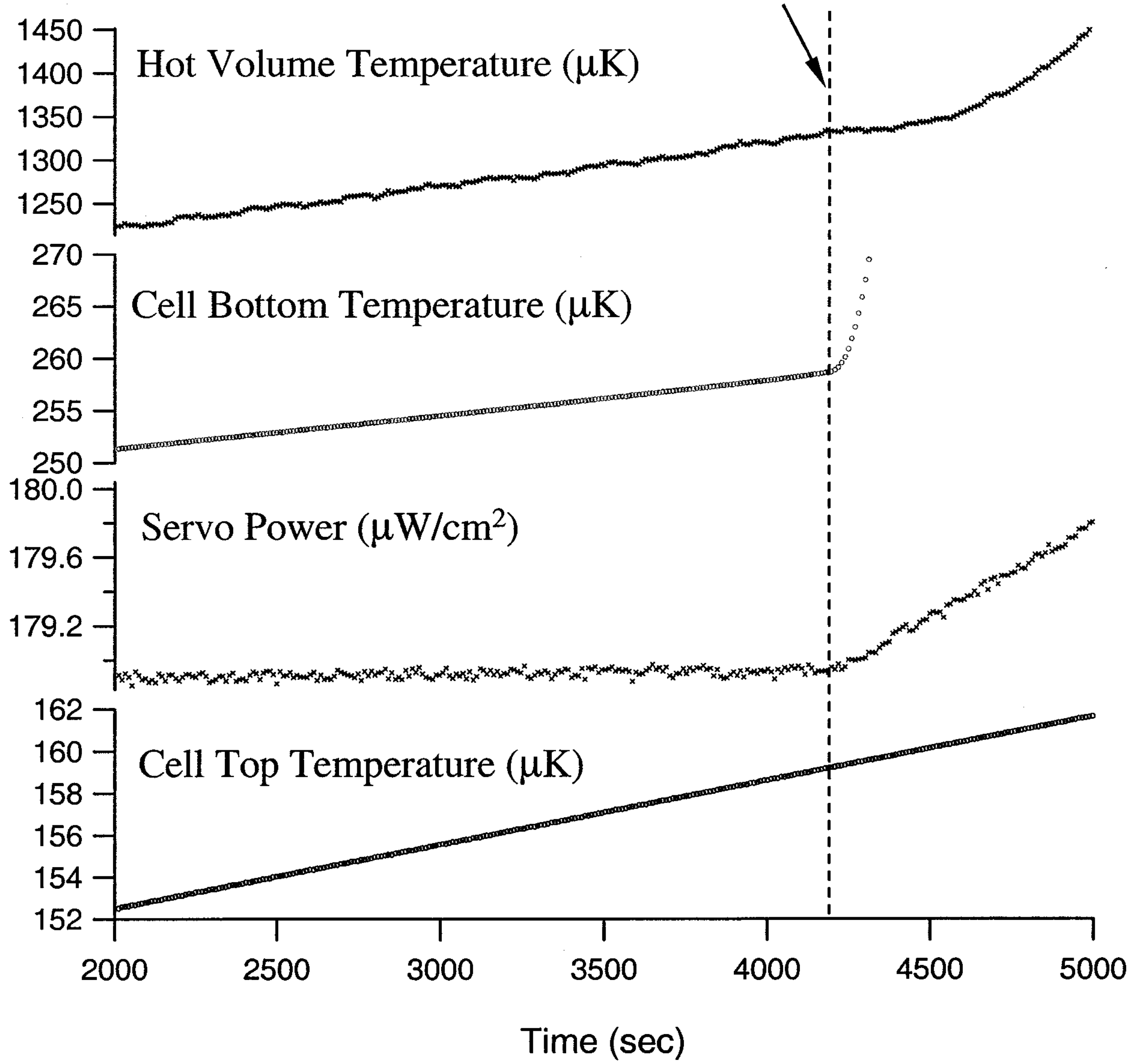
Heat Current: 10 mW/cm2
Ramp Rate: 3.17 nK/sec

Dissipation sets in @ the cell bottom boundary
$T_c(Q)$



Data Analysis - Calculation

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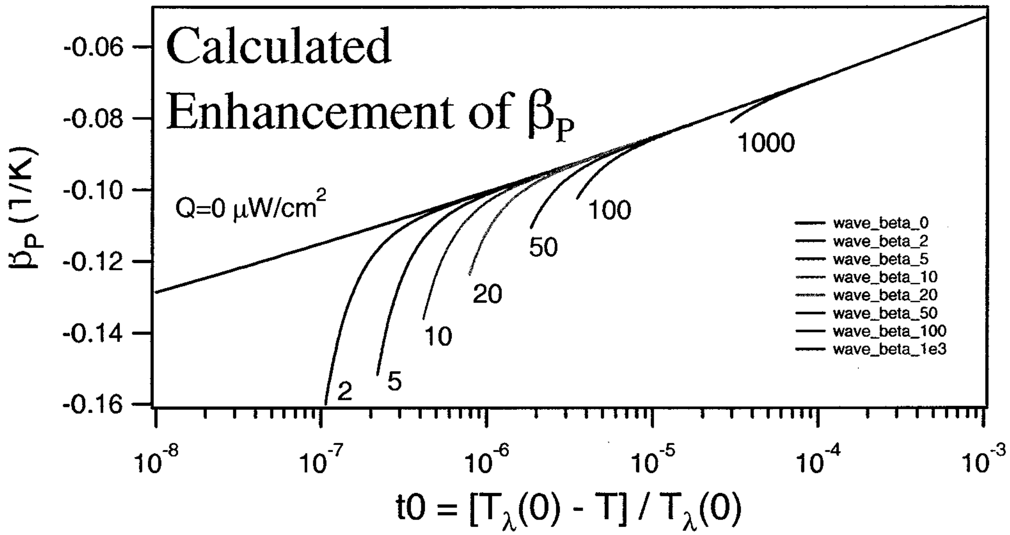
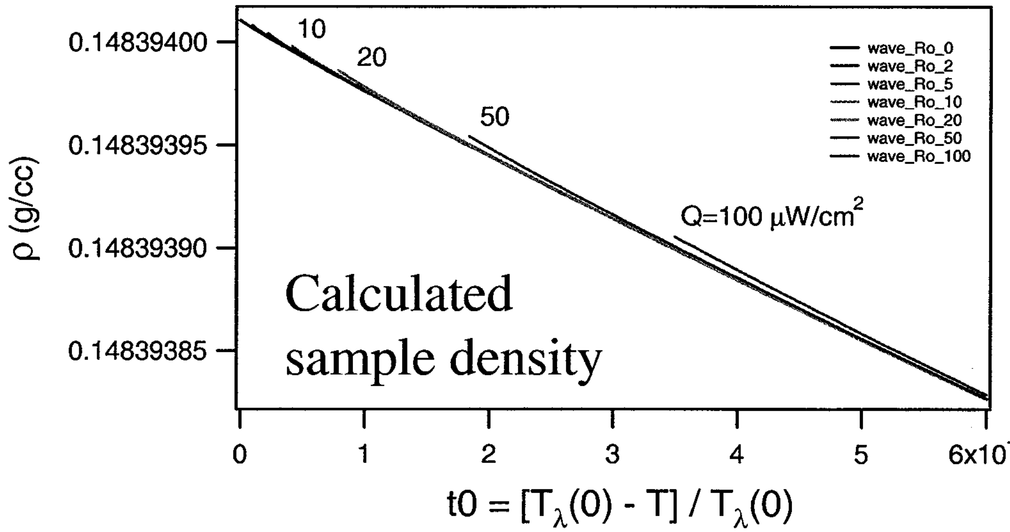
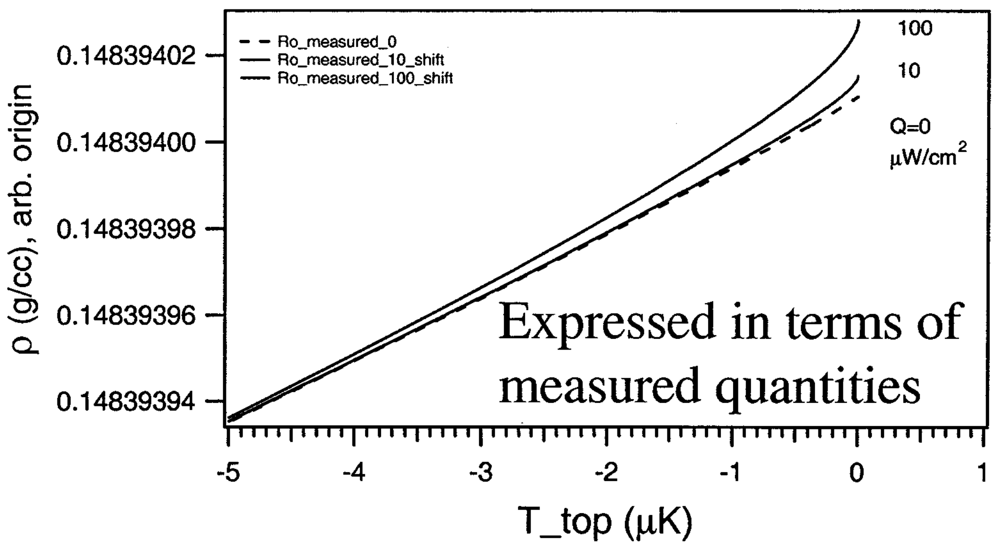




$$\Delta\beta_P(T,Q) = -t^{-\alpha} f(Q/Q_c)$$

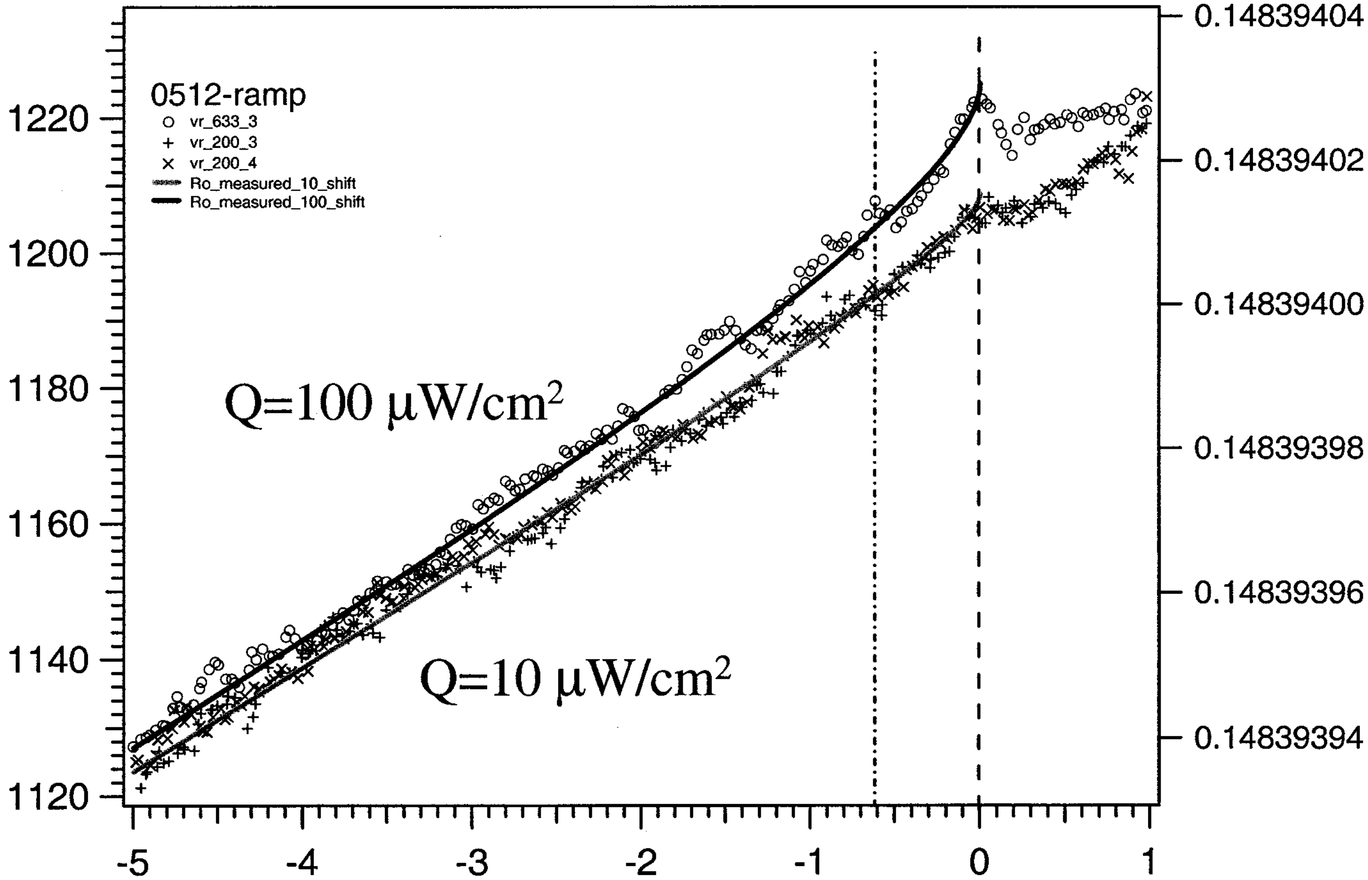
When $Q \ll Q_C$, $\quad f(Q/Q_c) = (A/600)(Q/Q_c)^2$

A=69 from Harter et al (experiment, A=6.25 from HD, 9.2 from GCH)



Data Analysis - Comparison

Hot Volume Temperature (μK)



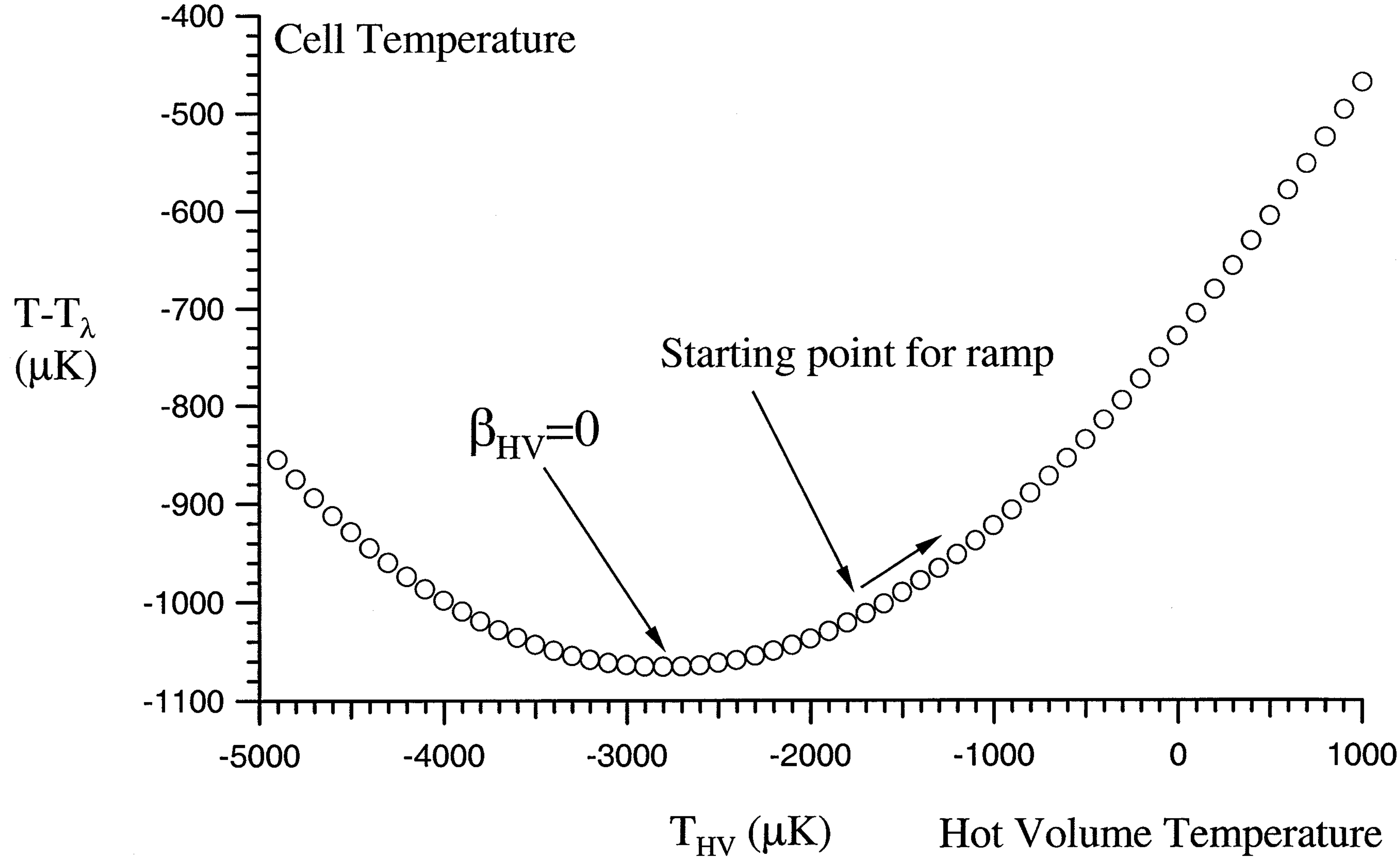
Density (g/cc) (Arbitrary Origin)

Cell Temperature: $T-T_\lambda(Q)$ (μK)

(Measured by the cell top thermometer)

Find T_{HV} where $\beta_{HV}=0$

From Measured β_{cell} of K. H. Mueller, G. Ahlers, and F. Pobell, β_{HV} can also be determined.



Discussions

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- We have performed experimental search for the enhancement of the thermal expansion coefficient by a heat current

- We have considered the rounding effect due to the variations in the local reduced temperature: t (z,Q)
  - T_λ variation due to gravity
  - T(t,z,Q) due to mutual friction
  - ΔT(t,Q), offset from T_top due to Kapitza resistance

  The last two factors lead to a larger temperature variation in the sample cell, therefore a larger rounding effect, for larger Q,

- Future work:
  - Measurements in reduced gravity
  - Increase the volume ratio (cell volume vs hot volume)

The superfluid transition in ^4He in the presence of a heat current (Q) provides an ideal system for the study of phase transitions under non-equilibrium, dynamical conditions. Many physical properties become nonlinear and Q-dependent near the transition temperature, T_λ. For instance, the heat capacity enhancement by a heat current was predicted theoretically[1], and observed experimentally[2]. Because the thermal expansion coefficient is a linear function of the specific heat near T_λ, both exhibit similar critical behaviors under equilibrium conditions. An enhancement of the thermal expansion coefficient is also expected if a similar relationship exists under non-equilibrium conditions. We report our experimental search of the enhancement of the thermal expansion of superfluid ^4He by a heat current ($0<Q<100\ \mu W/cm^2$). We conducted the measurements in a thermal conductivity cell at sample pressures of SVP and 21.2 bar. The measurements were also performed in a reduced gravity environment of 0.01g provided by the low-gravity simulator we have developed at JPL.

1. R. Haussmann and V. Dohm, Phys. Rev. Lett. 72, 3060 (1994); T.C.P. Chui et al., Phys. Rev. Lett. 77, 1793 (1996).
2. A.W. Harter et al., Phys. Rev. Lett. 84, 2195 (2000).